
daVinci
PROJECT
Canada's X PRIZE Contender

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AERO-HEATING ANALYSIS FOR DAVINCI SPACE PROJECT ROCKET BALLUTE

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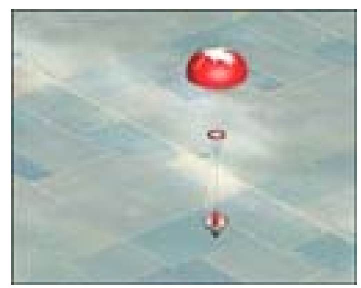
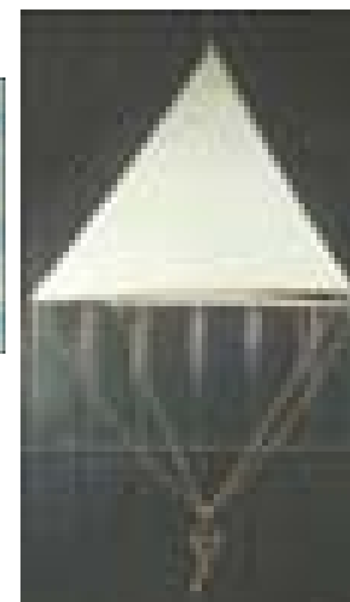
http://www.davinciproject.com





Prepared for NASA Thermo-Fluids Workshop
Huntsville, Alabama, Sept 10-14, 2001

DaVinci Project --- Introduction

<u>X-Project:</u> **objective is to fly a spacecraft with the three astronauts, to elevation >100 km and to do it TWICE during the two week period. No government funding is allowed.**
Award: 10 million $$$, 20 teams are now registered

<u>DaVinci Project:</u> **to meet this objective using "off-the shelf" commercial technologies. Utilize helium balloon for delivery to 80,000 ft, rocket on the tether, commercial multi-use engines. Rocket is returned using pressurized ballute to be deployed during the re-entry.**

Basic Idea of the Design

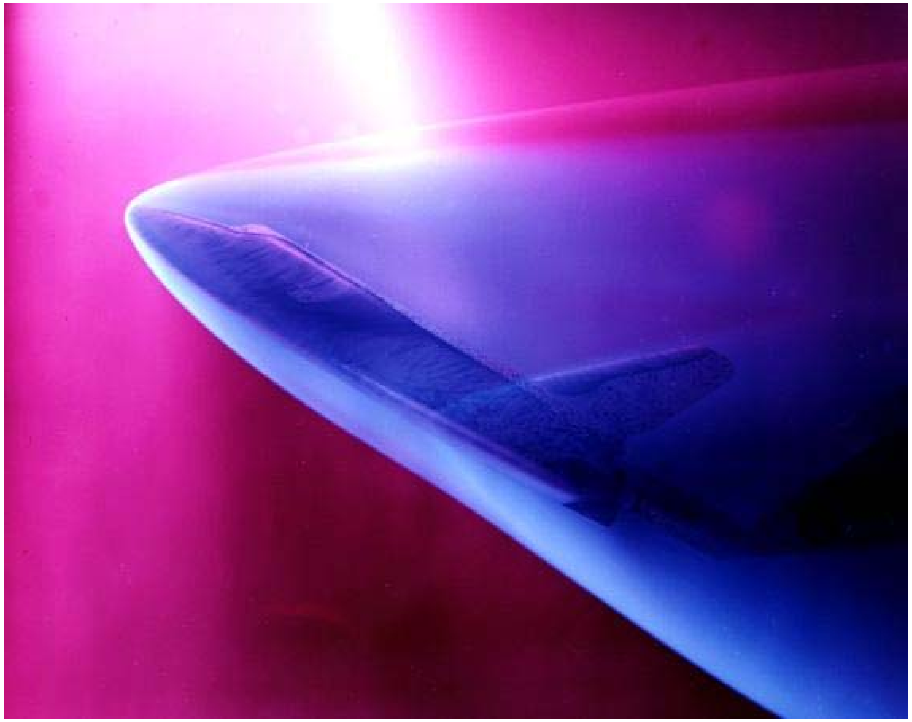
Follows Leonardo da Vinci parachute idea (see first title slide)

Rocket

Ballute 1: Peak temperatures

Ballute 2: High to medium Temperatures

Example: Shock wave visualization

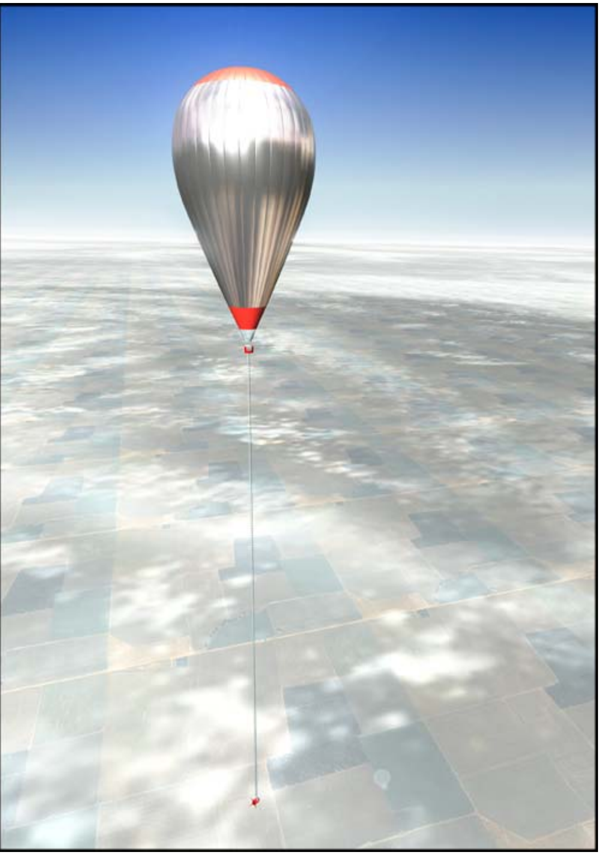


Bow shock wave is formed in front of the vehicle, internally pressurized ballutes assume thermal and pressure loads and protect the rocket and astronauts (rear) from excessive heat during re-entry.

Vehicle in Launch and re-entry mode

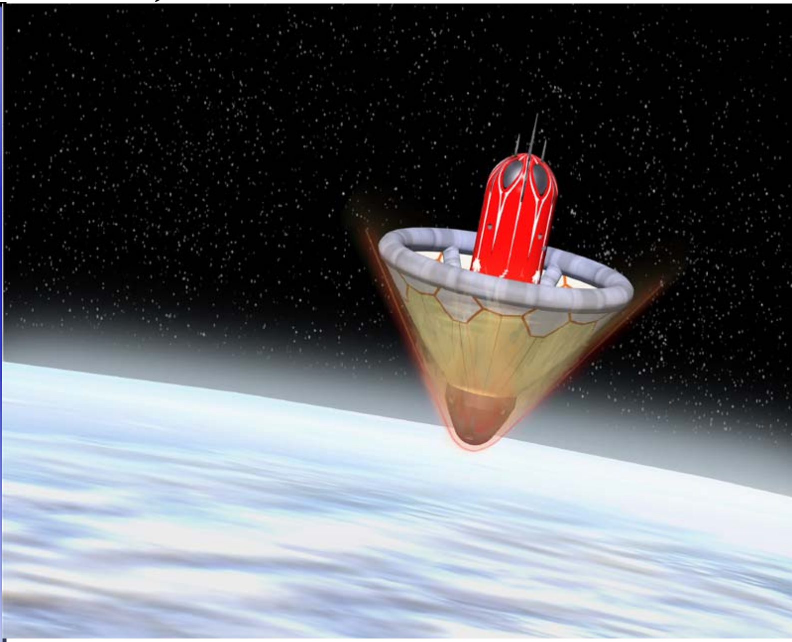
CFD CANADA

a)



b)

c)

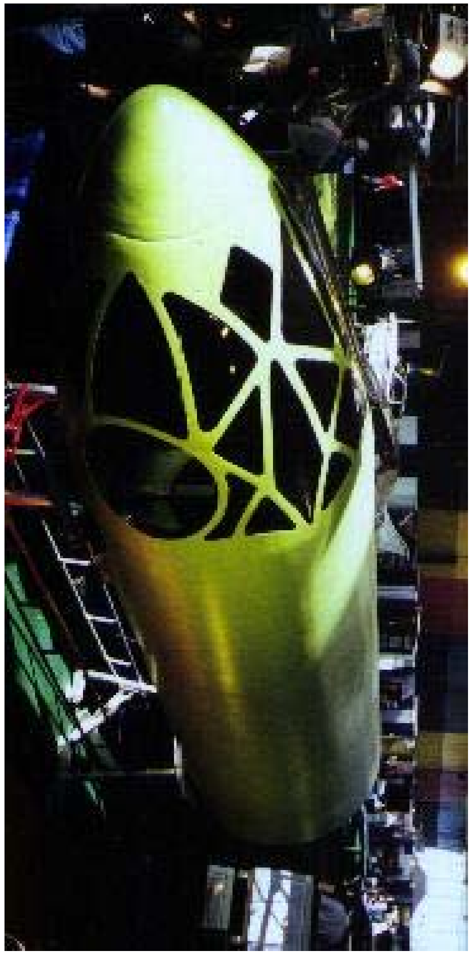


a) Vehicle tethered below the balloon
b) Close-up view of Vehicle
c) Vehicle re-entry with ballute deployed

Vehicle at Toronto Air Show (May, 2001)

Brian Feeney - Project Director

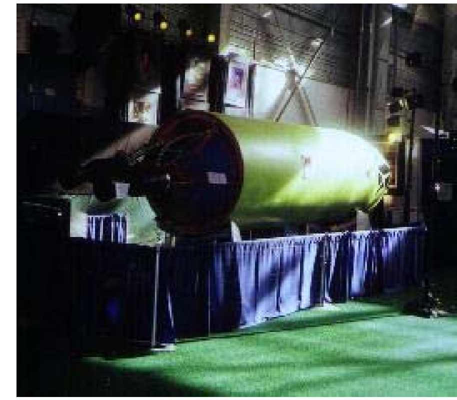
First conceptual prototype



Full scale prototype

daVinci Team

Assembled ballutes



In the exhibit hall

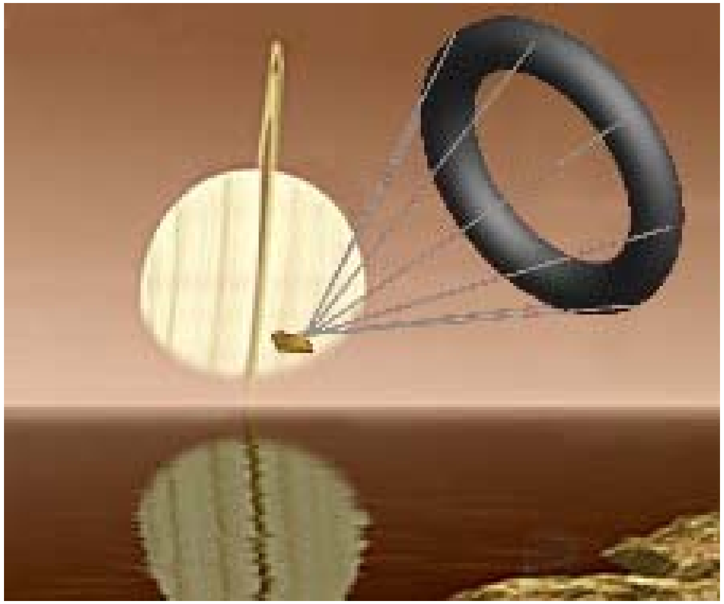
CONCEPTUAL DESIGN AND CFD

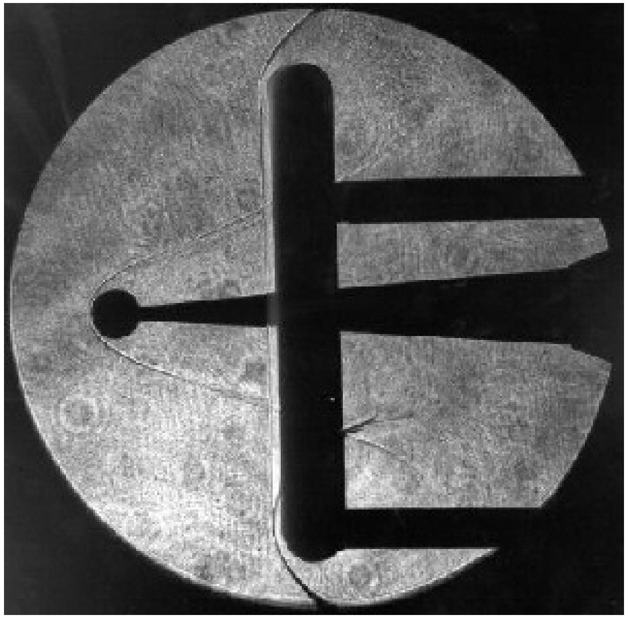
A)CFD REQUIRED ADDITIONAL DATASETS THAT DESIGNERS DID NOT HAVE INITIALLY, OR HAVE NOT CONSIDERED INITIALLY(ballute thickness, configuration, velocity estimations)
B) CFD ANSWERED SOME QUESTIONS THAT DESIGNERS HAD RAIZED (Cd, Pressure)
C)CFD RAIZED SET OF NEW QUESTIONS FOR DESIGNERS TO THINK ABOUT (STABILITY, LOADS, OVERHEATING)
D) CFD REQUIRED NEW AND MORE ACCURATE DATA (TRAJECTORY, GEOMETRY), ELEVATED DESIGN PROCESS TO A NEW LEVEL

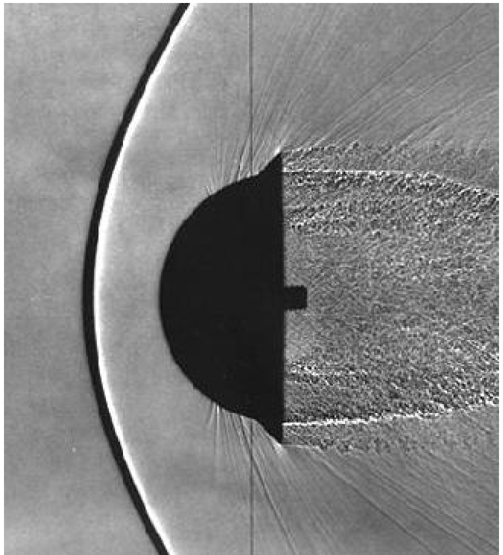
MAJOR “PRACTICAL” CFD DILLEMA → CHOICE OF CFD SOFTWARE and MODELS
ULTIMATELY WE USED WHAT WE COULD AFFORD AND WHAT WE KNEW.
CFD-ACE+ software package was utilized during the phase of conceptual design.
According to software developer (CFDRC) it can predict supersonic flows up to Mach =4.

We estimated air and flow conditions, temperature distributions, pressure field and drag coefficient Cd. These data helped to further modify the trajectory and to make new apogee and altitude estimations for the overall mission. These changes allowed us to minimize external thermal loads and to meet and exceed ballute material limitations.
At this point minor changes in ballute shape are no longer mission critical due to safety factor on material properties. Pressure forces on ballute were also estimated and weight requirements for helium gas were established.
MODE OF OPERATION: DESIGNERS PROVIDE INPUT--->CFD--->DISCUSSIONS ---> NEW INPUT --→ more CFD

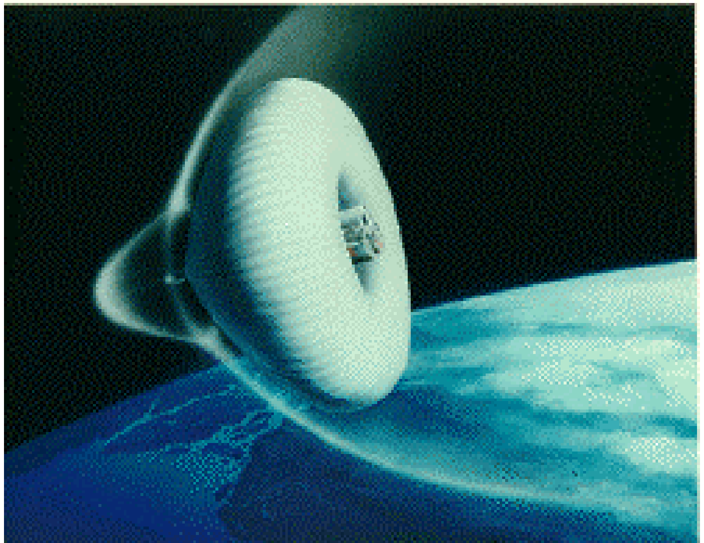
Ballutes - NASA JPL Conceptual Studies



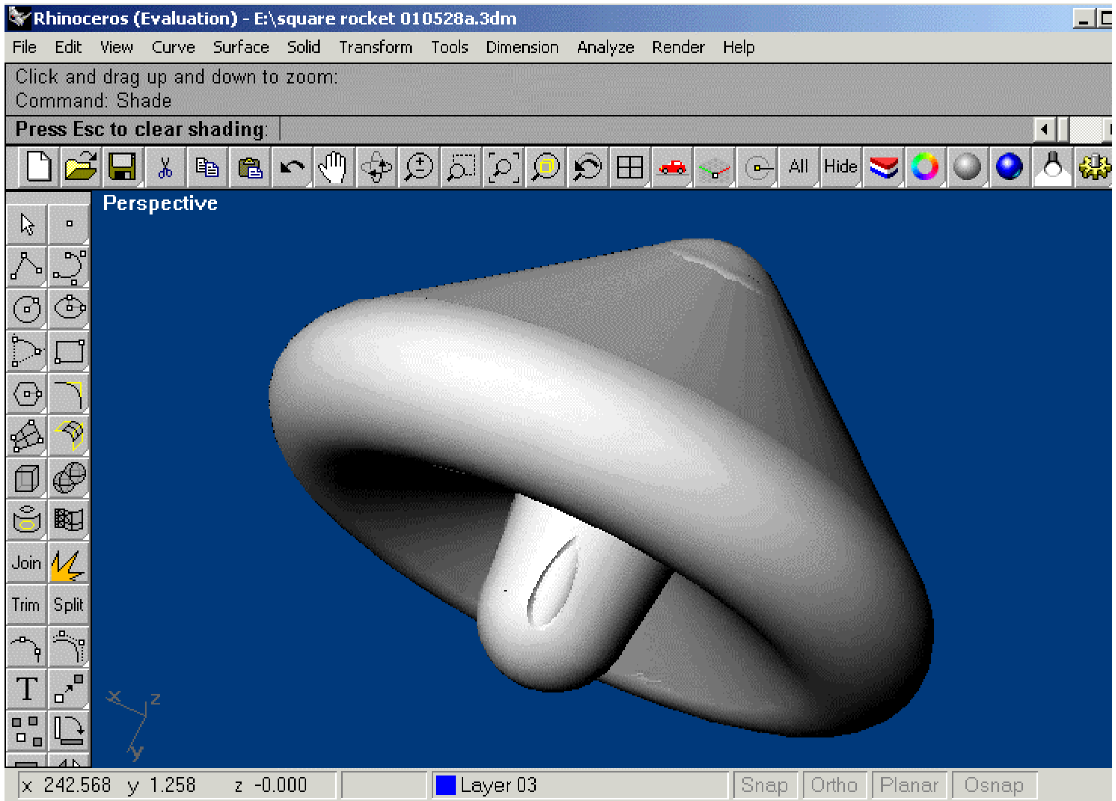




Bow shock visualization

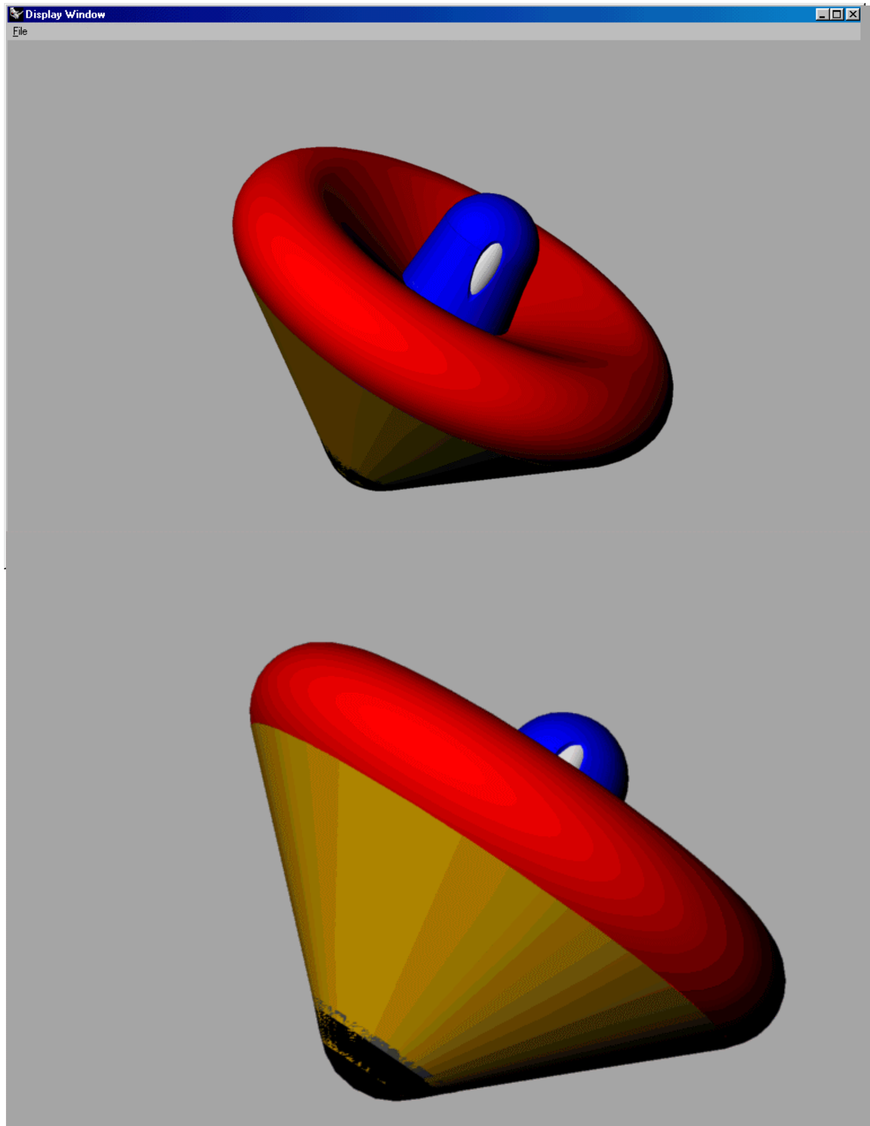


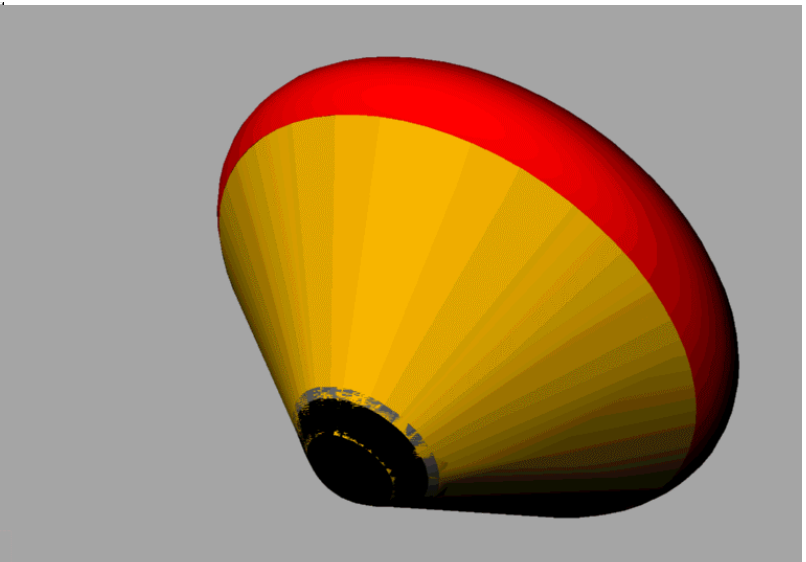
Rocket Ballute - Present Design



New Conceptual Configuration evolved as a result of engineering evaluation that followed CFD studies -- SECOND ITERATION OF CONCEPTUAL DESIGN

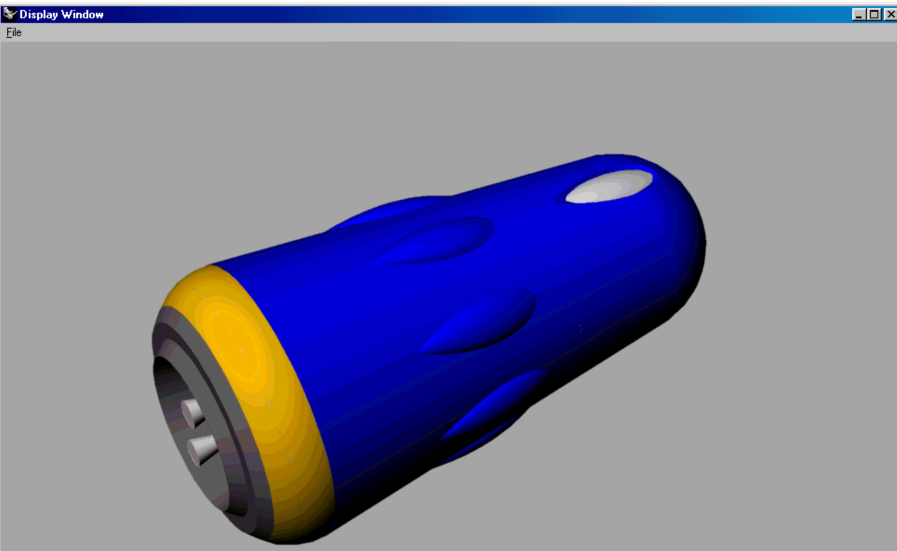
Rocket Ballute-Present Design

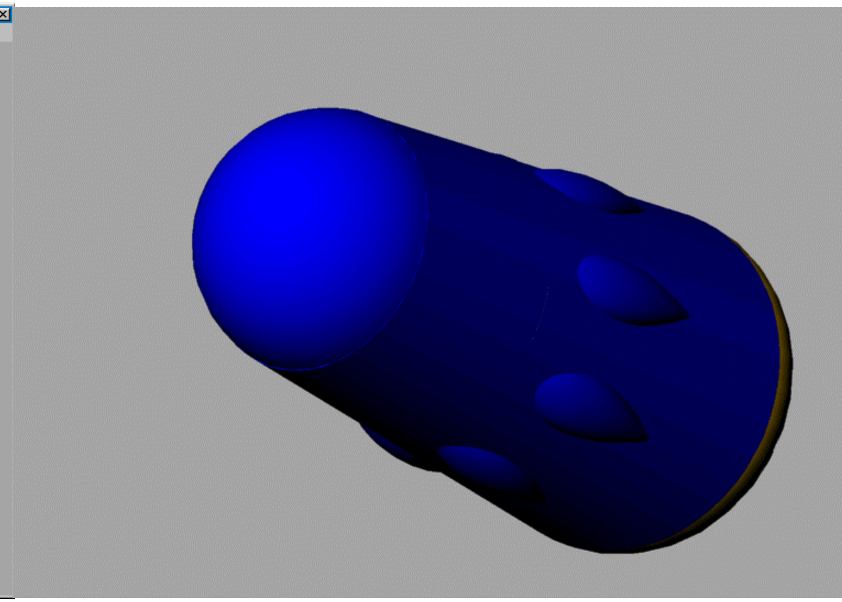


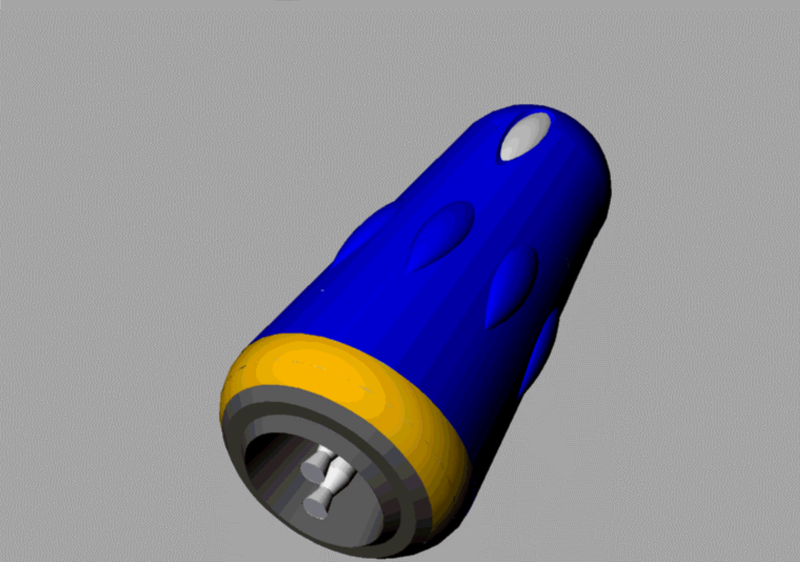


CHANGES:
-larger OD for ballute
-larger filled volume (front)
-longer to avoid
“wake closure” on capsule
-longer to move center of pressure away
from center of mass
<<CONFIGURATION IS FINALIZED>>

Rocket --- Present Design

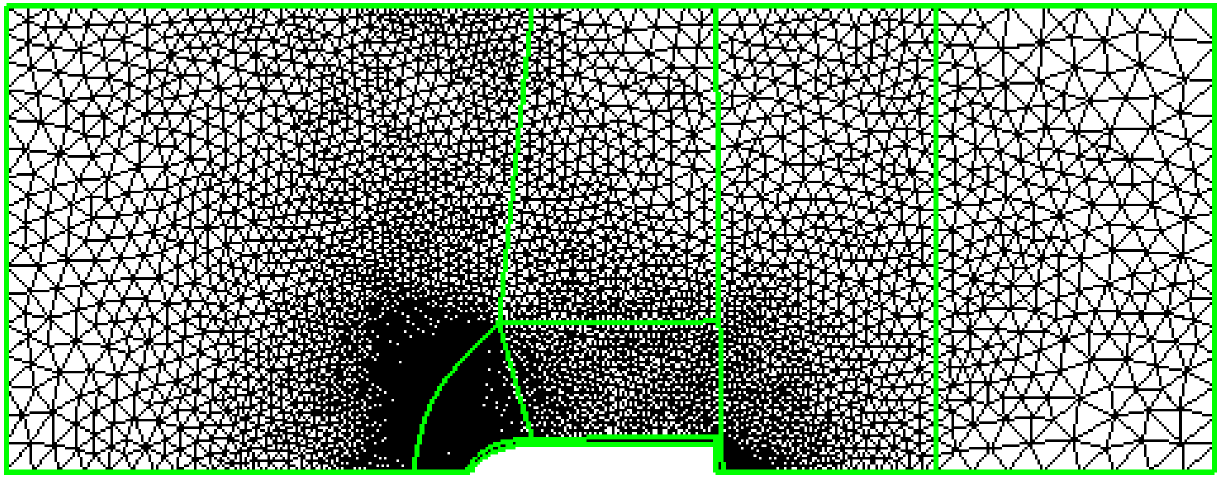






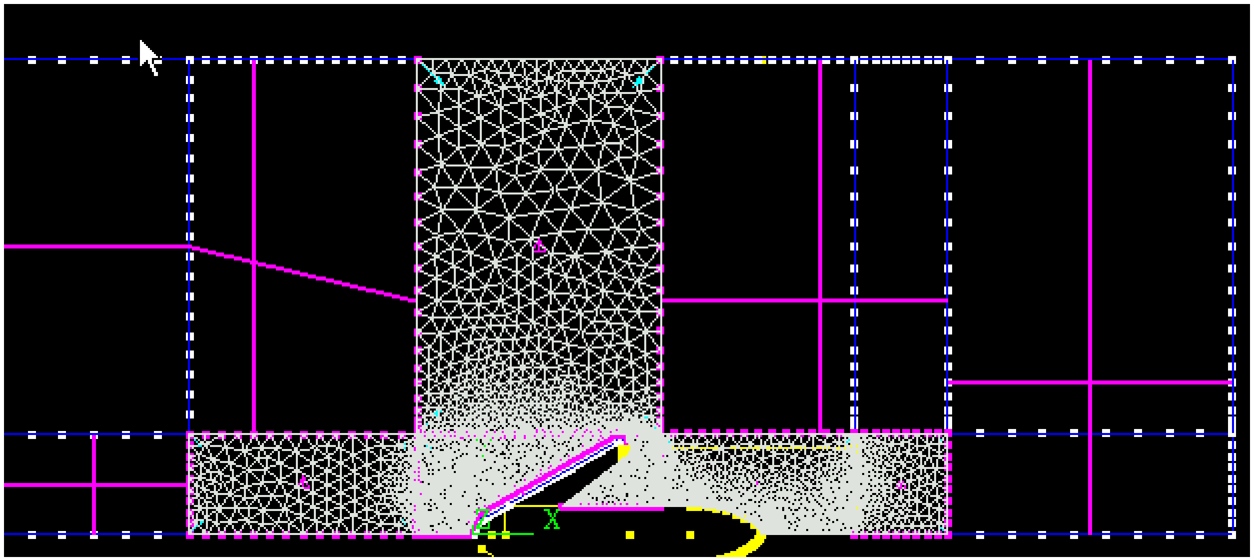
CHANGES:
-larger OD for rocket “base”
-larger front nose diameter and angle
SUBJECT TO SUBSEQUENT EVALUATION

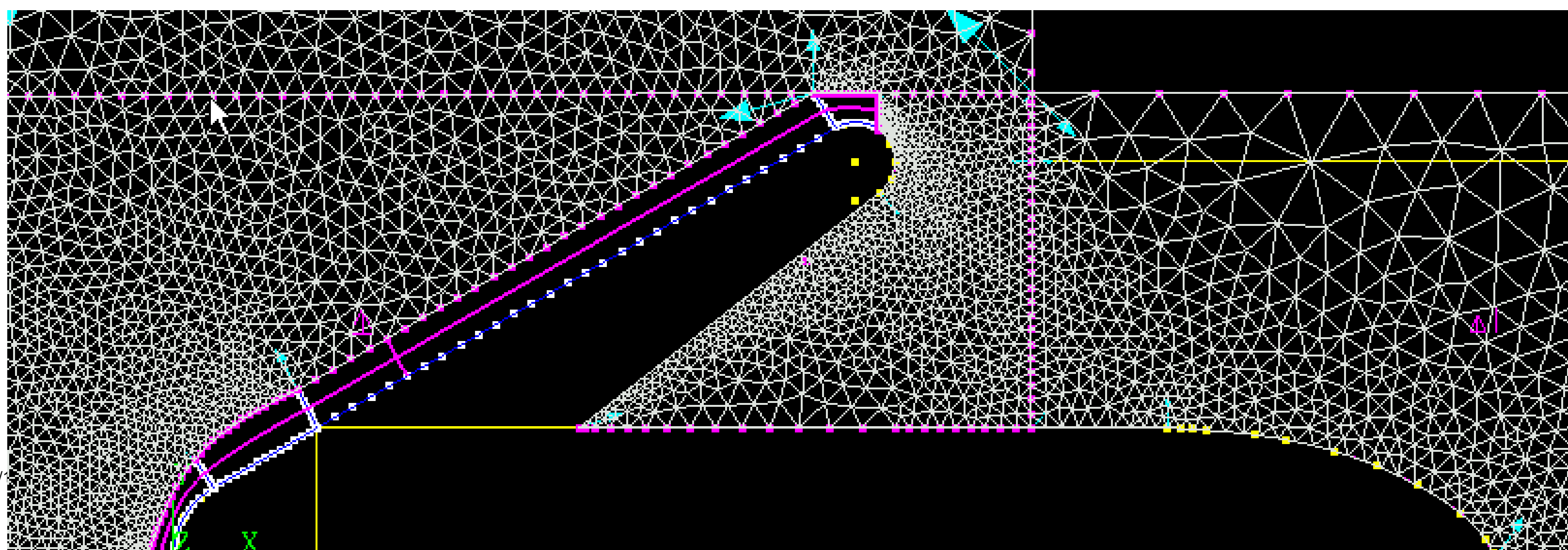
Computational Setup



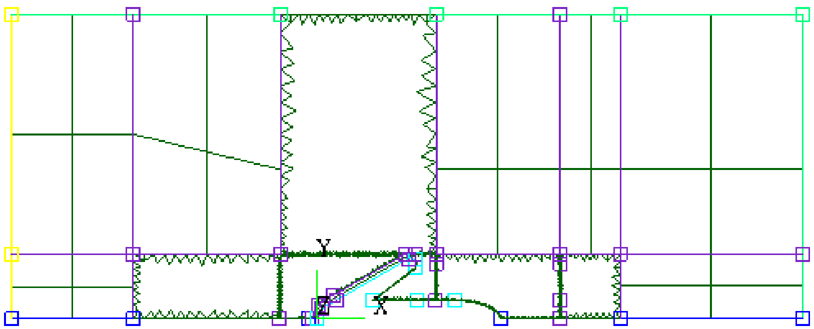
Rocket

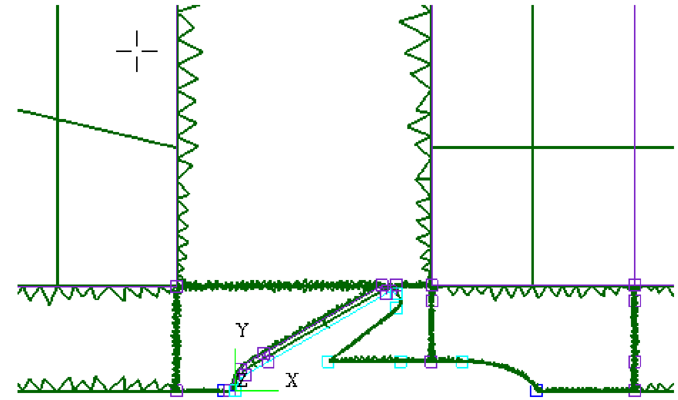
Hybrid S-U Gridding





Setup- Rocket Ballute





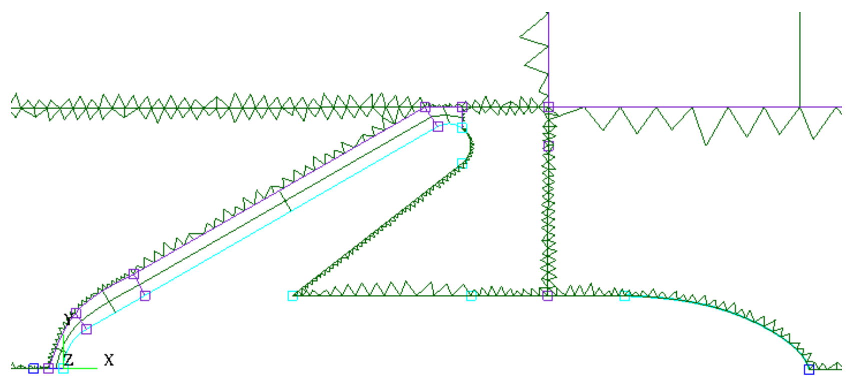
Output

Pressure Forces

	Name	Key	Type	X-axis	Y-axis
4	b1	464	Wall	1.722654E+04	-1.191149E+04
7	b1	471	Wall	1.861155E+04	-3.223037E+04
9	b2	491	Wall	2.857052E+05	-4.947670E+05
11	b3	492	Wall	5.738700E+03	-1.255066E+04
62	rb	583	Wall	-4.191336E-12	9.547799E+03
64	rbrear	585	Wall	3.005454E+03	1.291571E+04
75	rb	542	Wall	0.000000E+00	2.260614E+04
76	rb	543	Wall	-4.279382E-12	9.828310E+03
77	b4	598	Wall	1.397867E+04	6.904508E+02
78	b5s	599	Wall	3.215643E+04	-4.123918E+04

Shear Forces

	Name	Key	Type	X-axis	Y-axis
4	b1	464	Wall	2.884109E+01	2.981358E+01
7	b1	471	Wall	1.435156E+02	8.290480E+01
9	b2	491	Wall	1.887833E+03	1.088571E+03
11	b3	492	Wall	1.684699E+02	2.881604E+01
62	rb	583	Wall	-3.849444E+00	3.784508E-01
64	rbrear	585	Wall	-2.980826E+00	3.375424E-01
75	rb	542	Wall	-2.468475E+00	8.473813E-02
76	rb	543	Wall	-3.492539E+00	-2.613778E-02
77	b4	598	Wall	1.106551E+01	-6.542686E+00
78	b5s	599	Wall	2.188292E+00	1.945553E+00



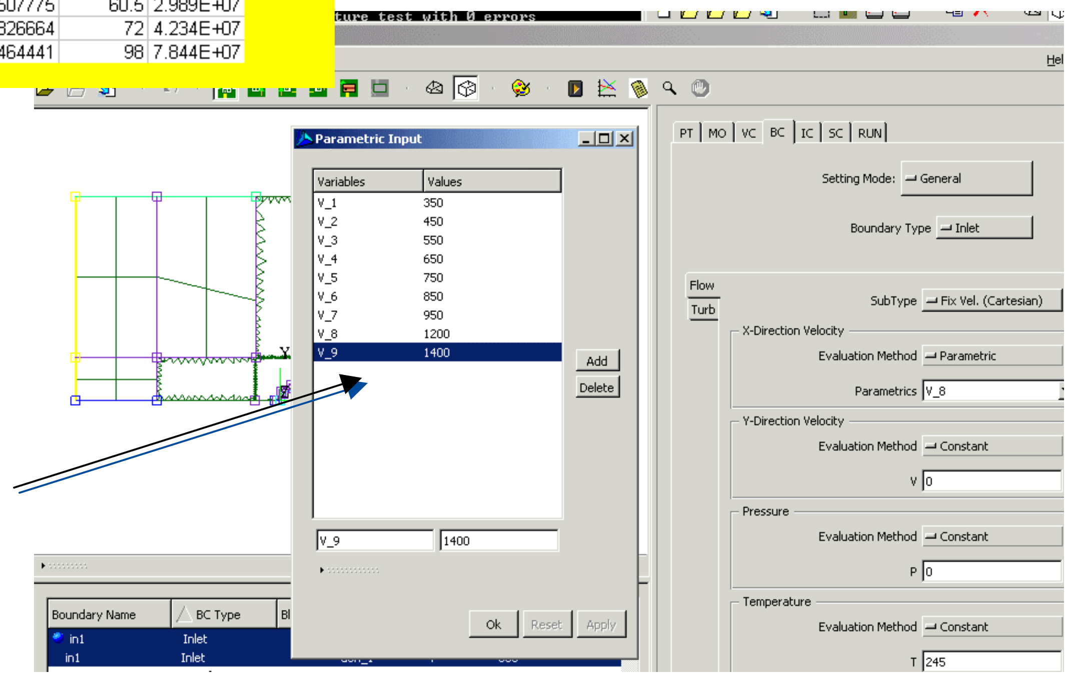
Problem Setup -velocities

K-eps RNG Turbulence Model, with the following inlet conditions: example P=20E3 Pa, T=245 (low altitude)

P, Pa	T, K	mu	RHO	Beta	Tu_free	Velocity	M	K	D
20,000	245	1.56885E-05	0.284732	0.2	0.01	350	1.11611	6.125	3.064E+05
20,000	245	1.56885E-05	0.284732	0.2	0.01	450	1.434999	10.125	8.373E+05
20,000	245	1.56885E-05	0.284732	0.2	0.01	550	1.753888	15.125	1.868E+06
20,000	245	1.56885E-05	0.284732	0.2	0.01	650	2.072776	21.125	3.645E+06
20,000	245	1.56885E-05	0.284732	0.2	0.01	750	2.391665	28.125	6.460E+06
20,000	245	1.56885E-05	0.284732	0.2	0.01	850	2.710554	36.125	1.066E+07
20,000	245	1.56885E-05	0.284732	0.2	0.01	950	3.029442	45.125	1.663E+07
20,000	245	1.56885E-05	0.284732	0.2	0.01	1000	3.188887	50	2.042E+07
20,000	245	1.56885E-05	0.284732	0.2	0.01	1100	3.507775	60.5	2.989E+07
20,000	245	1.56885E-05	0.284732	0.2	0.01	1200	3.826664	72	4.234E+07
20,000	245	1.56885E-05	0.284732	0.2	0.01	1400	4.464441	98	7.844E+07

Inlet velocity conditions:

we start computations with lower flow (V=350..450 m/s) and then use converged solutions from lower velocity case as start-up for higher velocity case.
For a given altitude (pressure, Temperature) we run range of velocity conditions between 350…1400 m/s

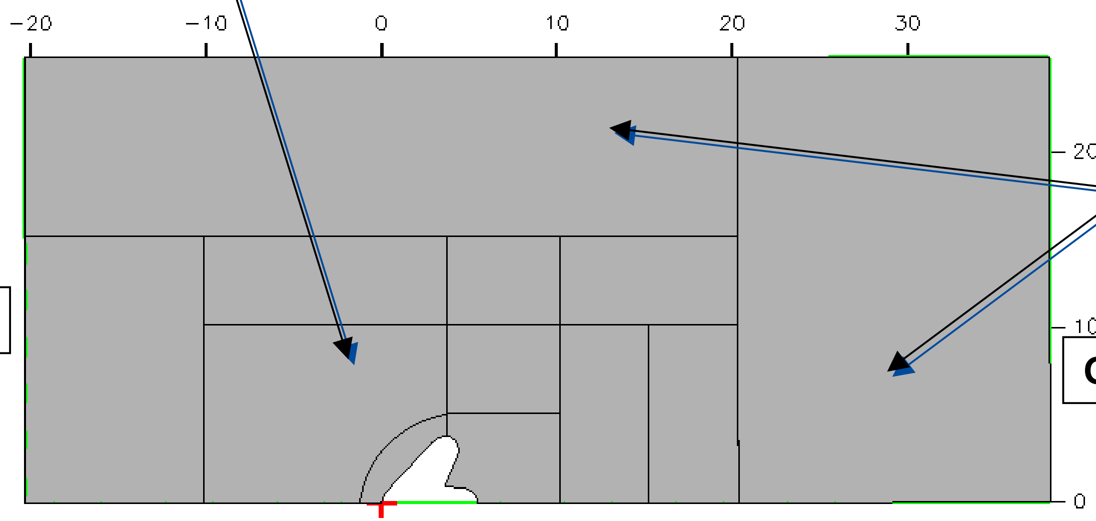


Boundary Conditions

Computational Domain: approximately 12K nodes

Most Robust model:
IC: previous solution for all fields
inlet: fixed inlet velocity Vfree
outlet2: fixed far filed velocity Vfree
outlet1: extrapolated pressure

Outlet 2



"extra" segments were added in process to better support far field conditions

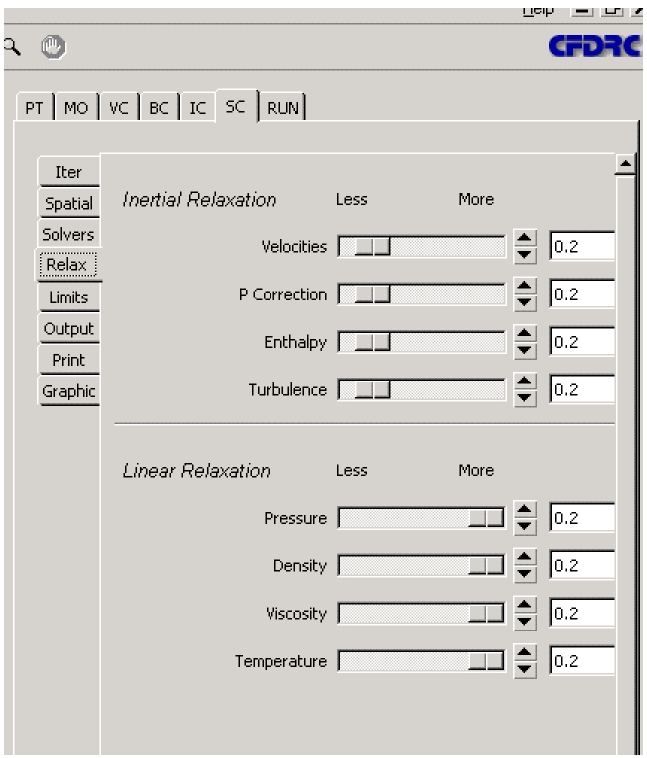
inlet

Outlet 1

symmetry

Also considered:
outlet2: fixed pressure, P=0, or extrapolated pressure
outlet1: fixed pressure, P=0
If any node at the outlet has velocity <M, extrapolated condition will lead to divergence

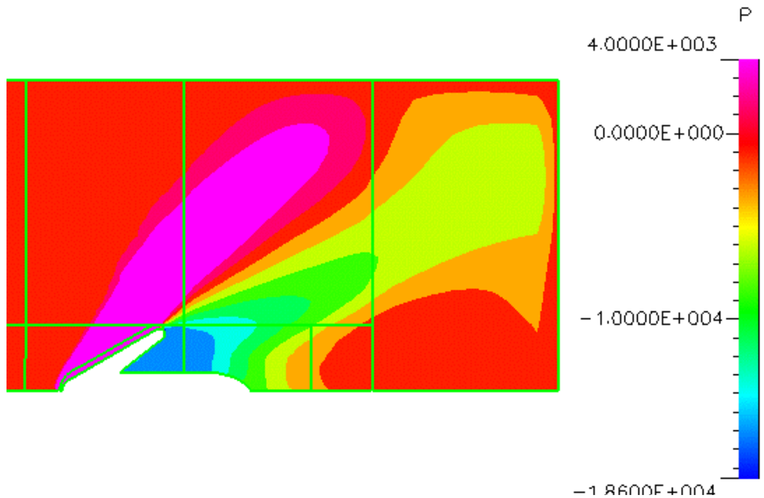
BCs, Solution and Relaxation

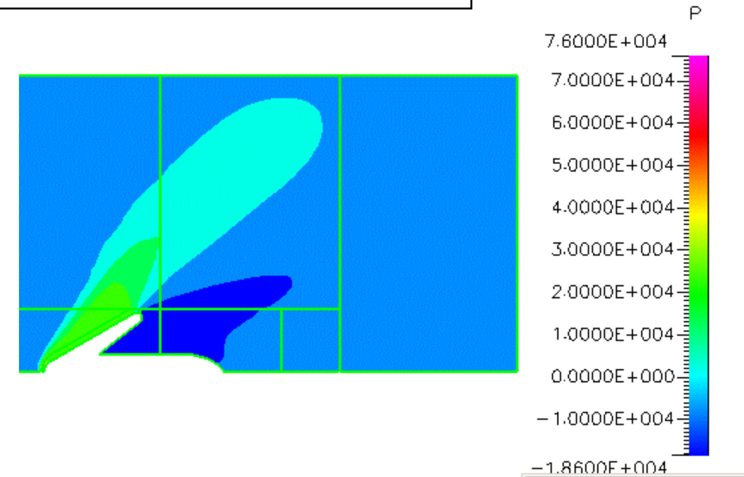


-OUTLET BOUNDARY CONDITIONS and CONVERGENCE at different velocities
-startup solution with 100 m/s ramp
-linear relaxation for pressure, density, viscosity and temperature in the range 0.7…0.2
[note that we use pressure based code in this study]

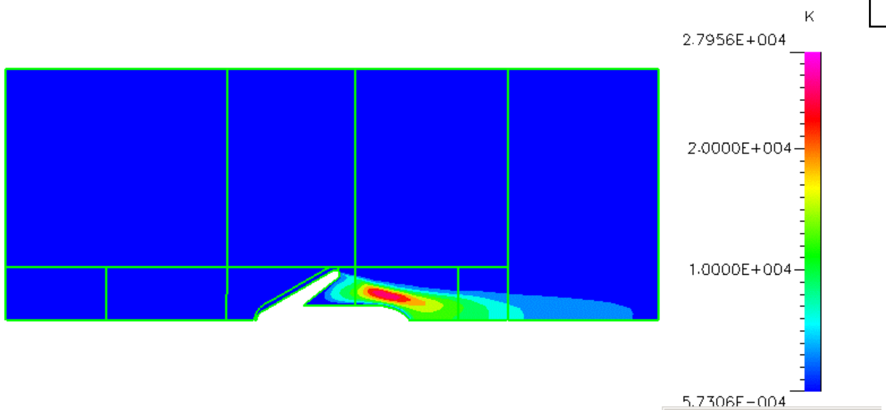
First Results: Vinlet=550 m/s

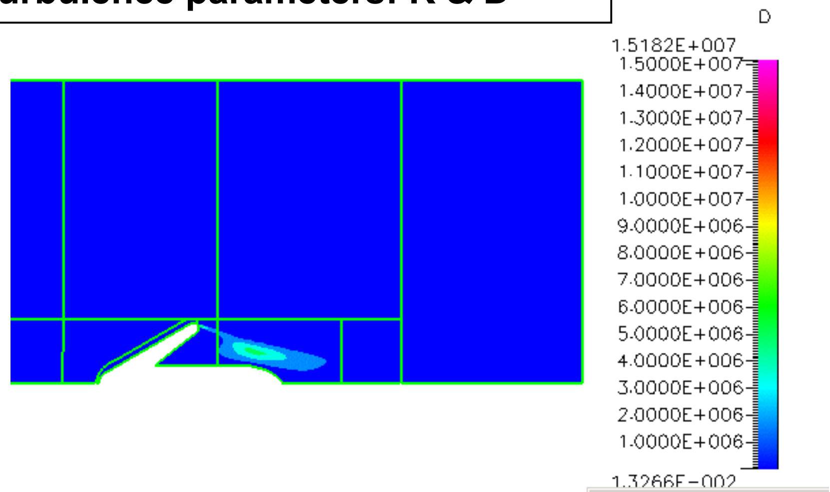
Pressure fields



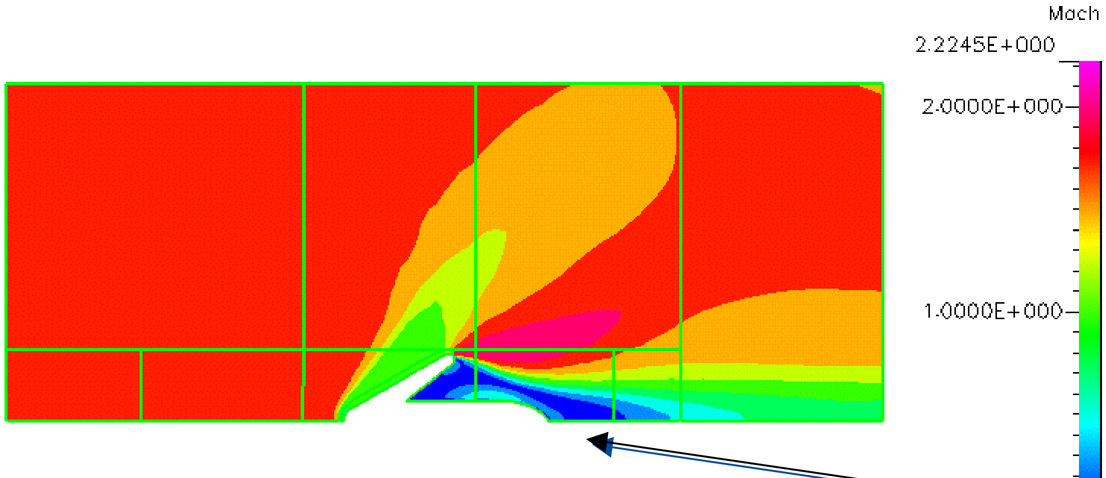


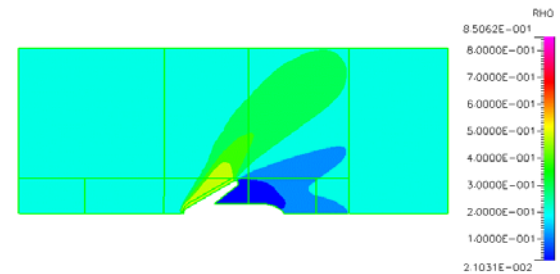
Turbulence parameters: K & D



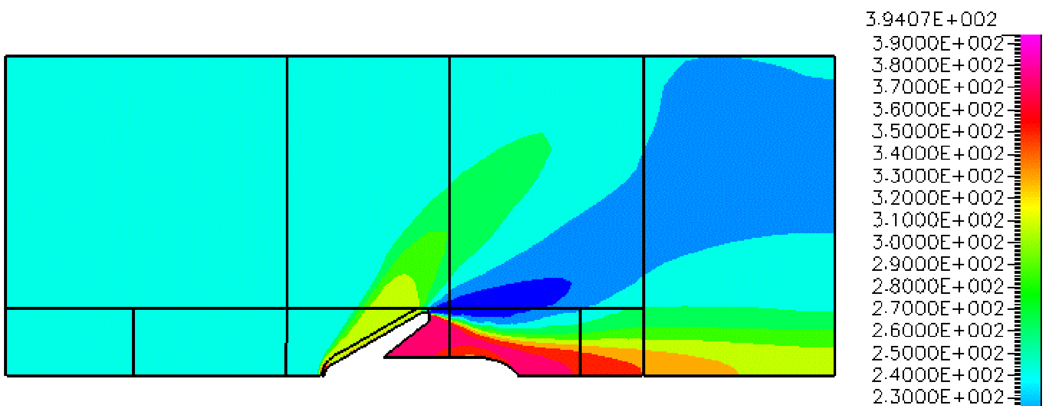


Mach Numbers and Temperatures



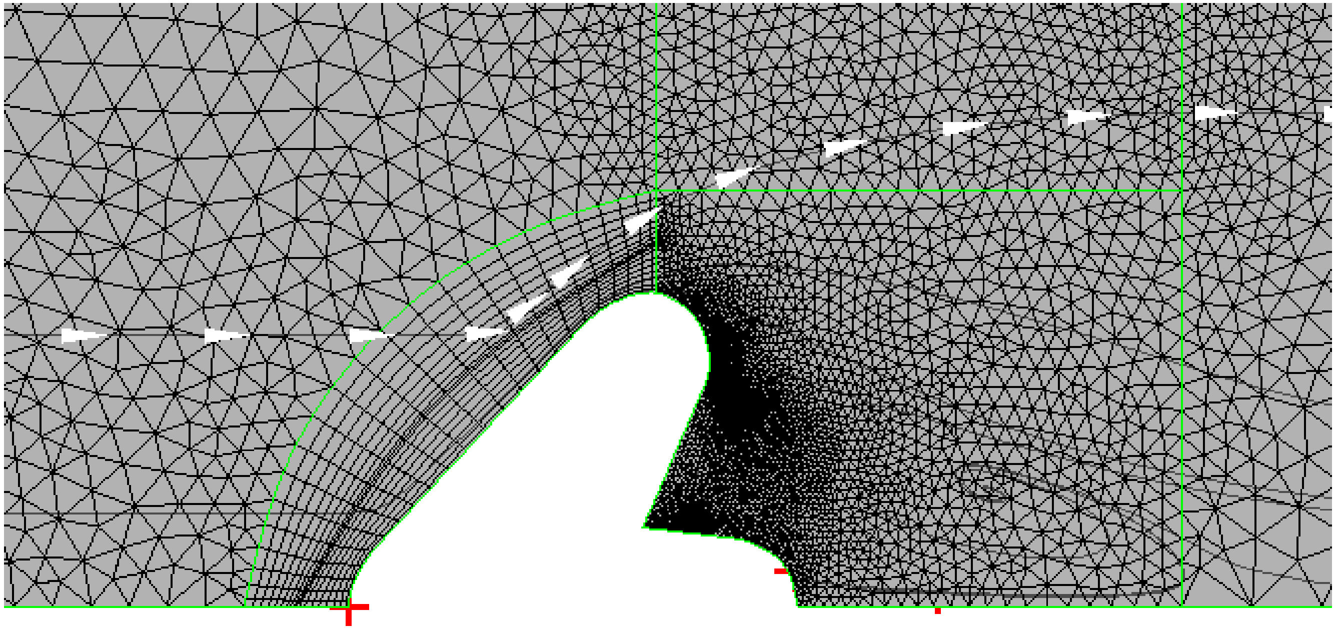


Recirculation Zone --flow impingement on the capsule. Consequently this finding lead to rocket ballute re-design.



Excessive heating in the wake!
We continue investigating this phenomena , suspect bug in software or in our model setup.

Second Design Iteration, Rballute=1.5meters

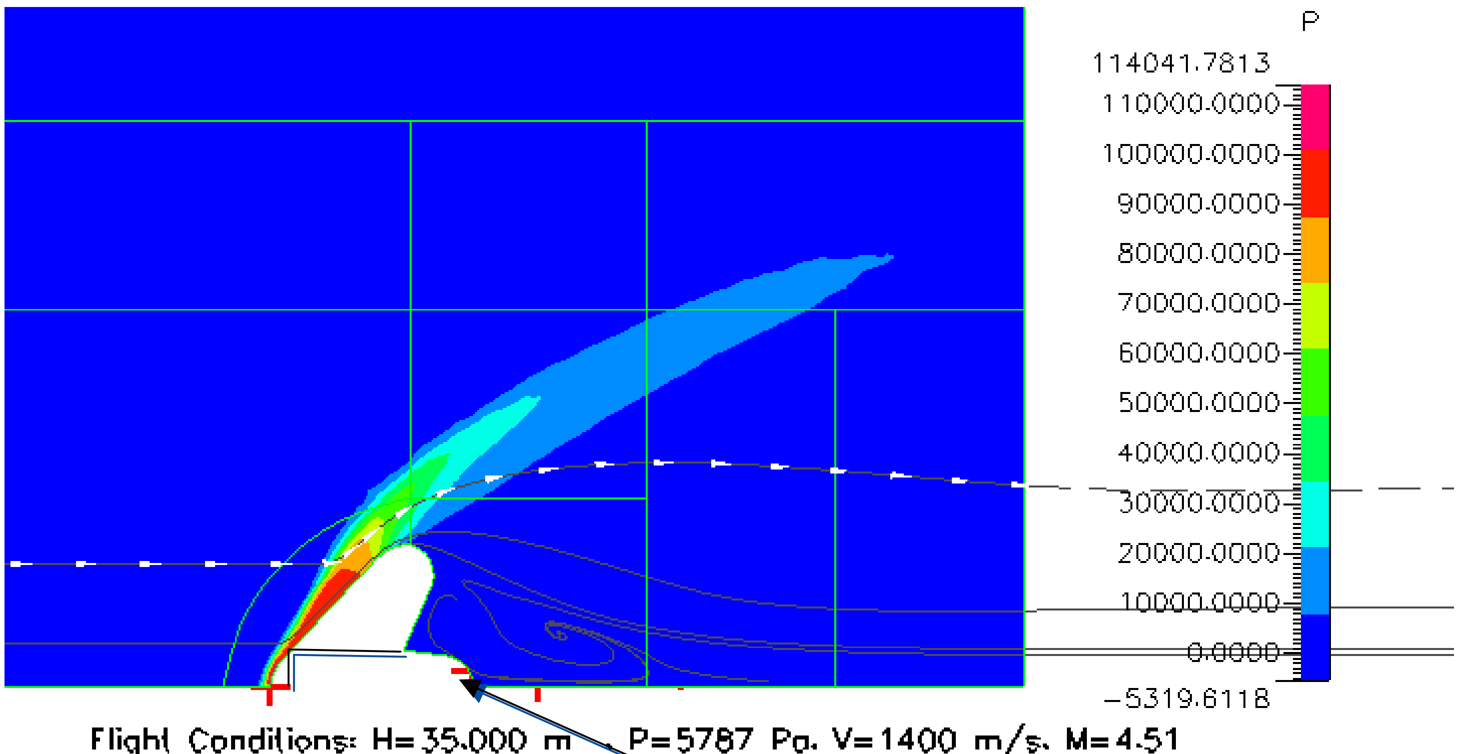


Hybrid structured-unstructured grid near ballute

Bow Shock (pressure) distribution

Worst case scenario considered: M=4.5 at H=35 km

Max pressure is close to 15 psi: defines requirements for ballute pressurization , helim mass for on-board storage

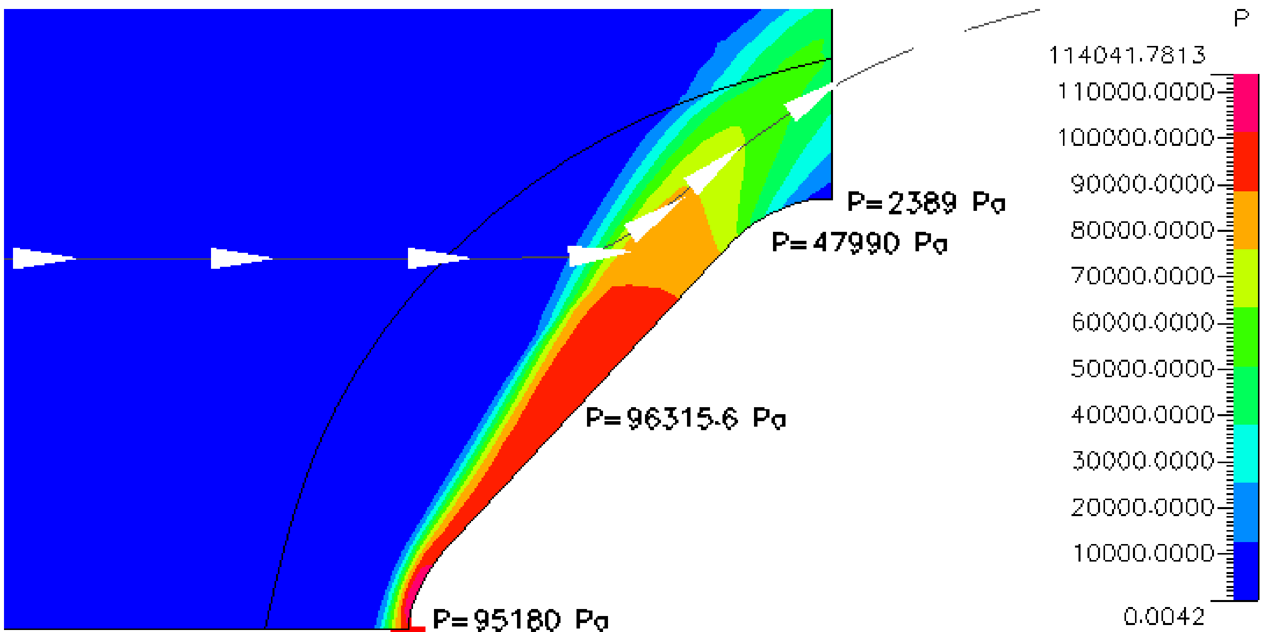


capsule

Note much shorter rocket body and larger aspect ratio. Correspondingly wake is now much larger and covers entire capsule with astronauts.

Pressure Loads for Ballute Calculation

Worst case scenario considered: M=4.5 at H=35 km



Flight Conditions: H=35.000 m , P=5787 Pa, V=1400 m/s, M=4.51

Rmax=1.5 m, Area=7.38, Ftot=6.14E5, Cd(calc)=1.009

FIRST ITERATION: maximum load conditions

Aerodynamics - Cd estimation

CFD CANADA

Peak Flight Conditions Zone

H (km)	P[Pa]	T [K]
30	11680	230
35	5730	244
40	2920	258
44	1750	267

Cd=2F/A/[RHO*V2]**

Forces, N on segments, for 1 radian

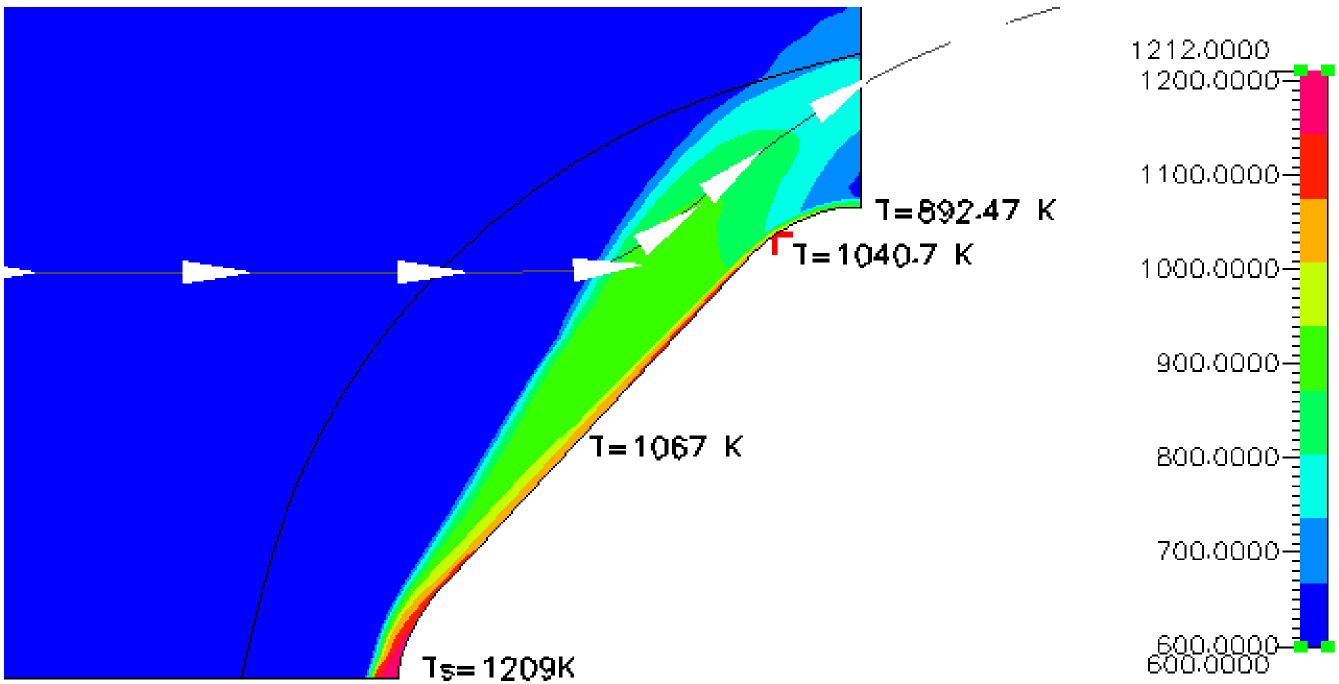
1.27E+03						1.08E+03
2.04E+02						1.9872
5.90E+02						5.81E+02
6.44E+02						6.63E+02
1.92E+03						2.12E+03
5.08E+01						5.80E+01
1.72E+02						2.11E+02
3.00E+02						3.03E+02
9.54E+04	Newton	Total				**9.78E+04**
Total=6.28*9.54E4		**599112**				6.14E+05
Area=	7.38				Velocity=1400 m/s	
Cd=2F/[RHO*V**2]		0.984915				**1.009966**
0.08281	Rho_BY_SA		RHO_CODE		0.084106	

Total force

Cd

Forebody Heating - Ballute

Worst case scenario considered: M=4.5 at H=35 km



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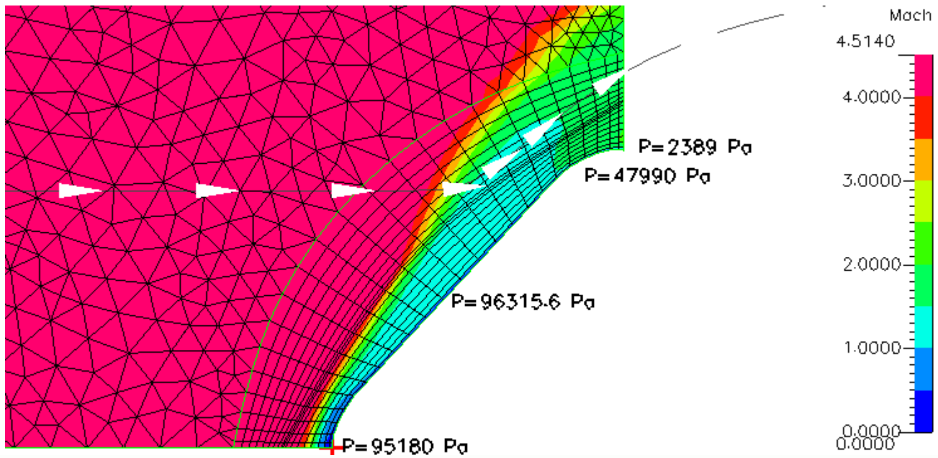
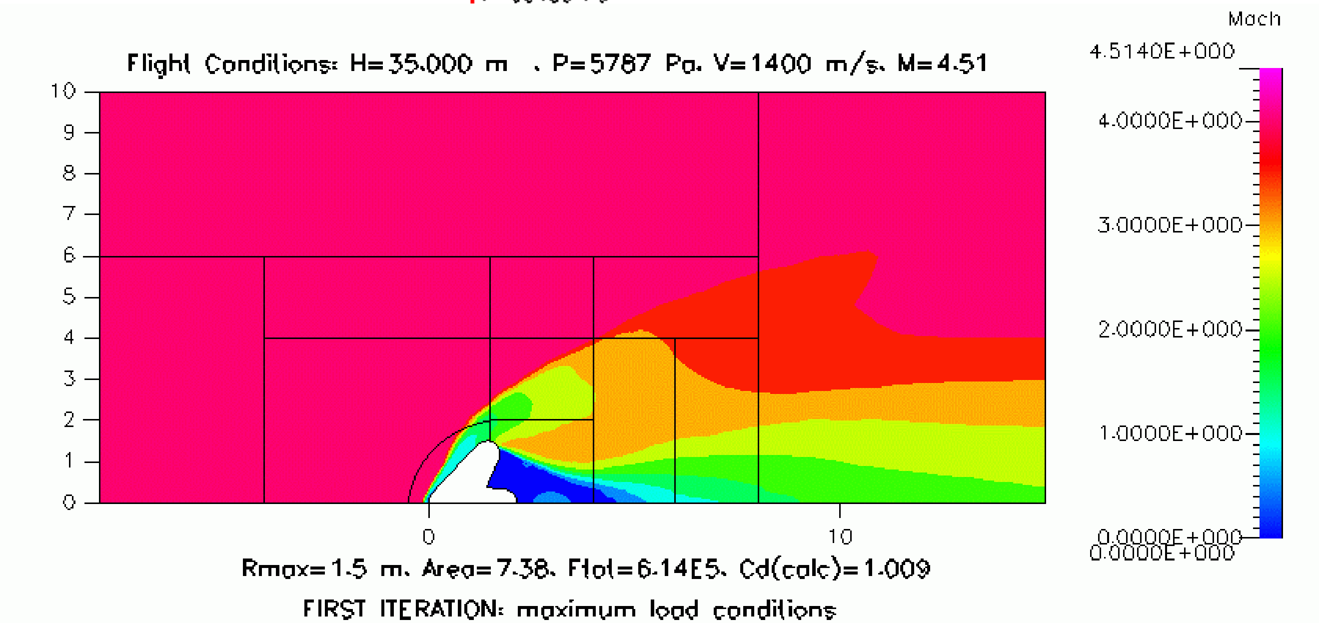
FIRST ITERATION: maximum load conditions

Mach Number

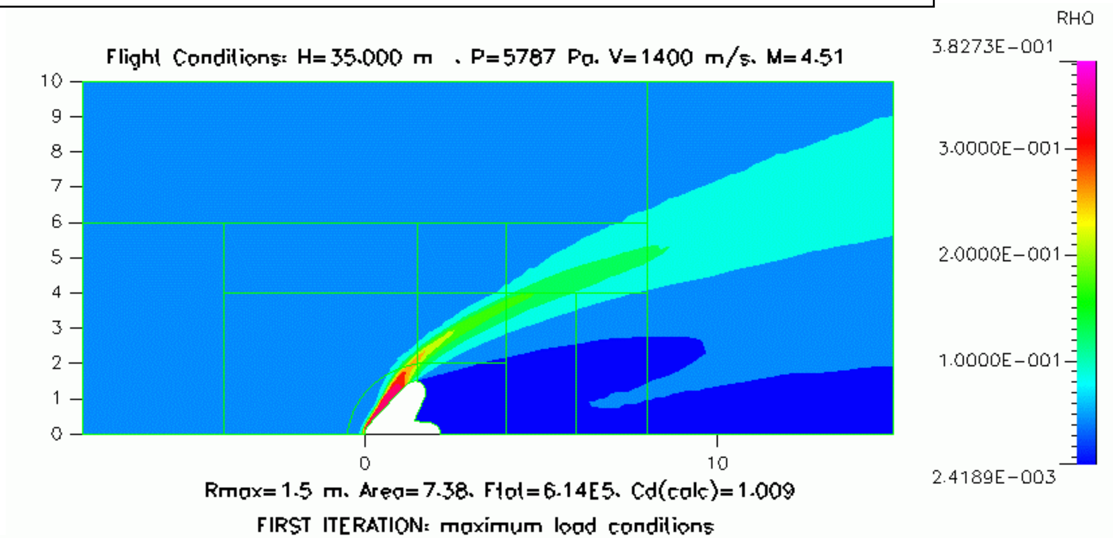


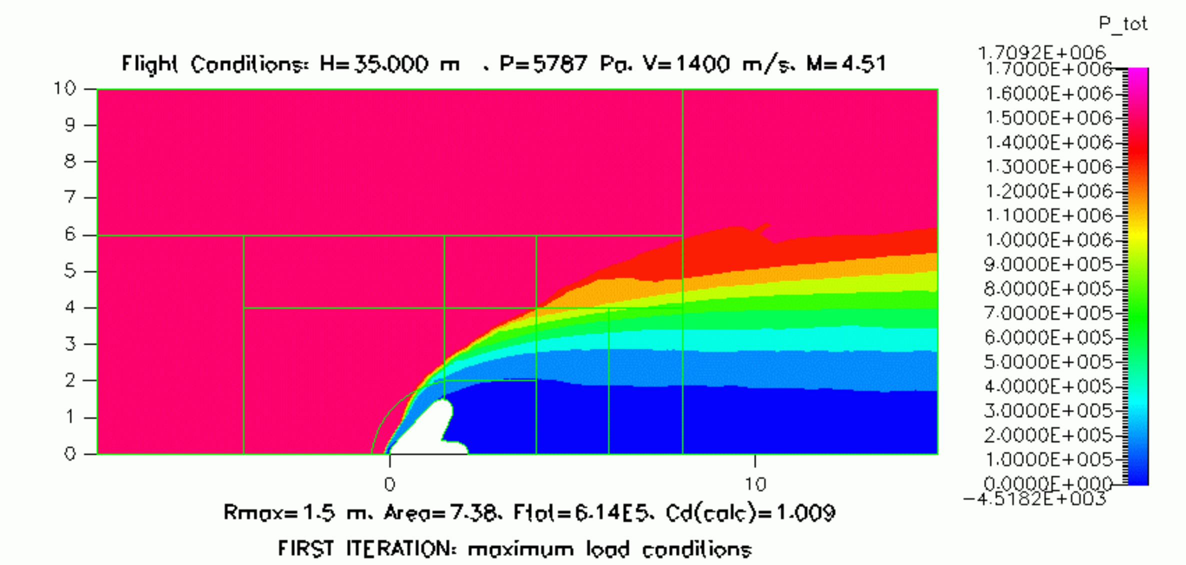


Worst case scenario considered: M=4.5 at H=35 km

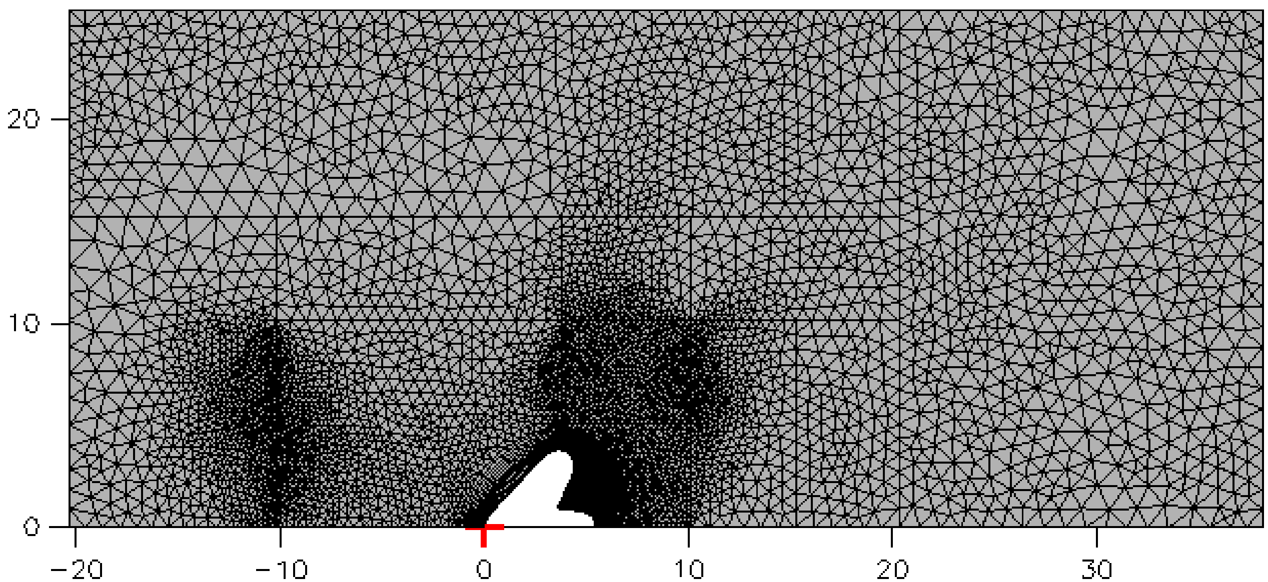
Density and Total Pressure

Worst case scenario considered: M=4.5 at H=35 km



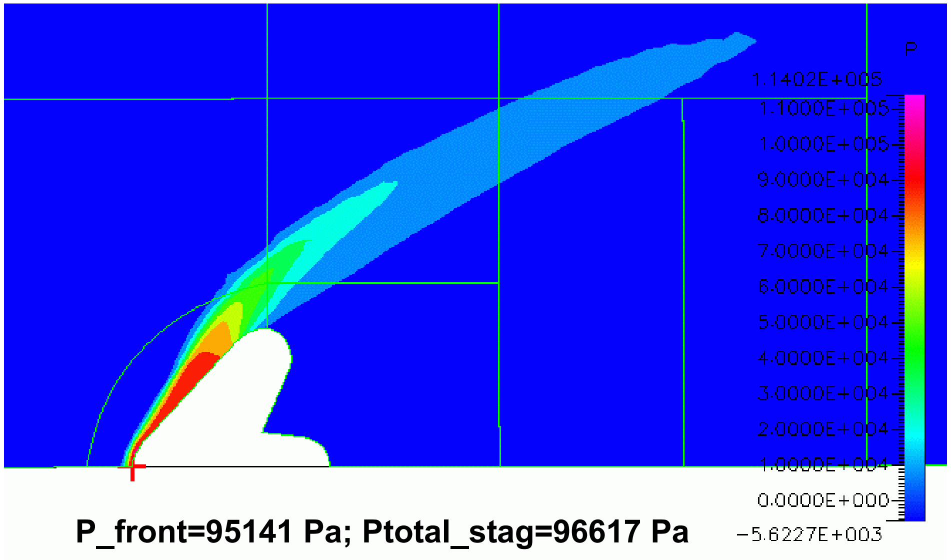


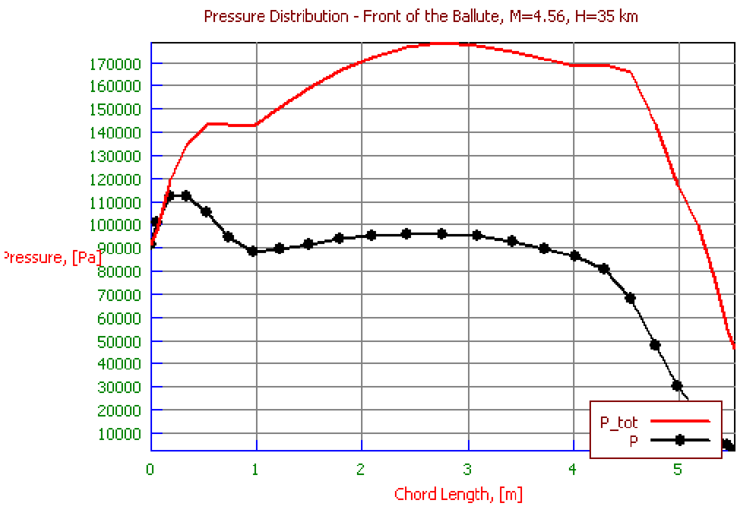
Third Iteration: Increased Ballute Outer Radius Rmax=3.78 meters



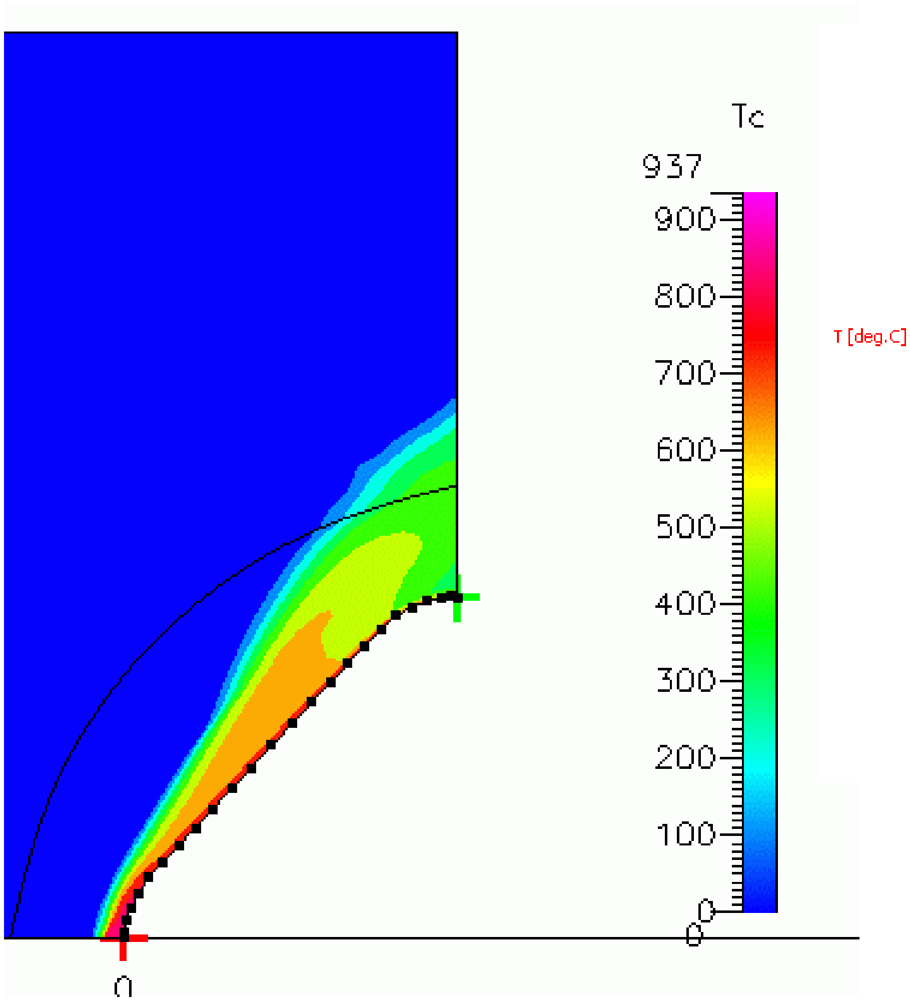
Worst case scenario considered: M=4.5 at H=35 km

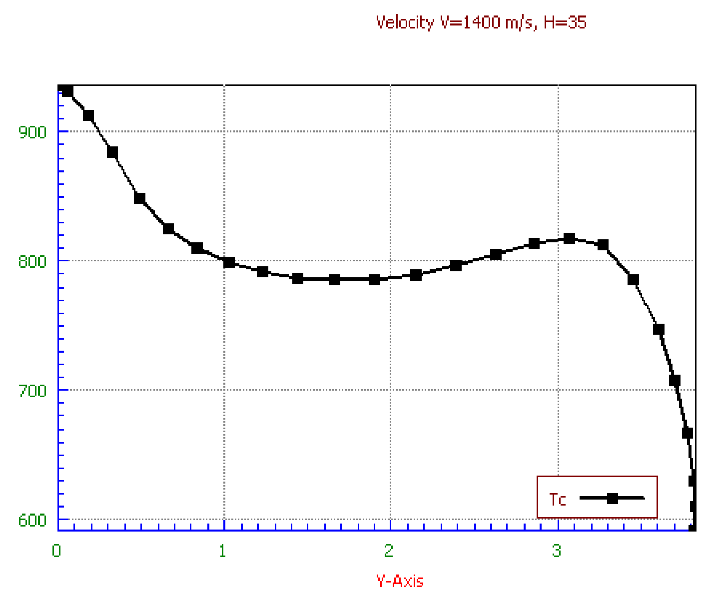
Pressure distribution





Forebody Heating - Ballute

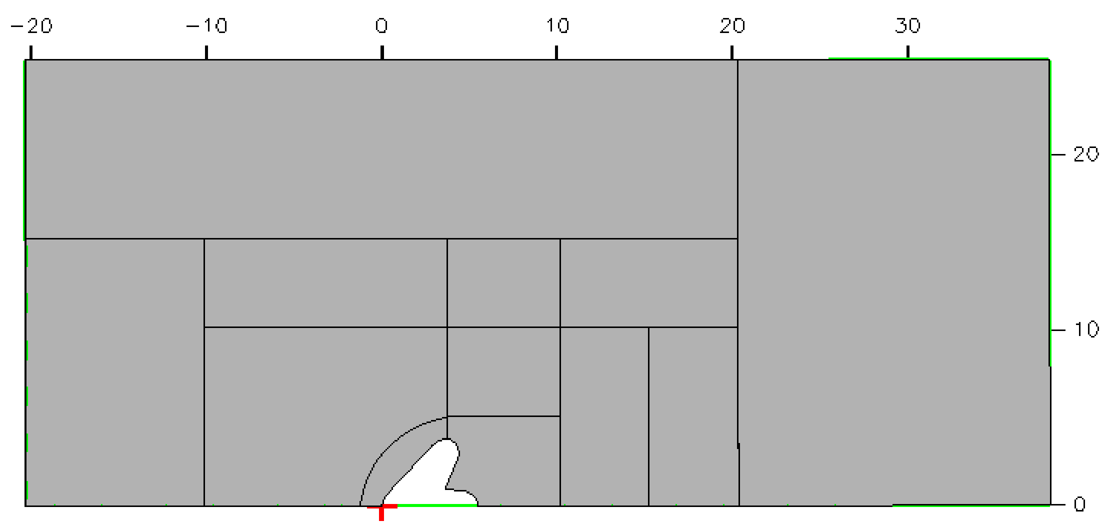




Tmax=1209K, Tmax=936.2 C;

Peak loads shown in previous section are on the limit of available resources and material properties.

Here we present results for three different trajectories: with apogees of 110, 120 and 130 km. According to preliminary ballistic analyses this corresponds with maximum velocities of 925 , 110 and 1091 m/s at approximate altitude of 47 km.



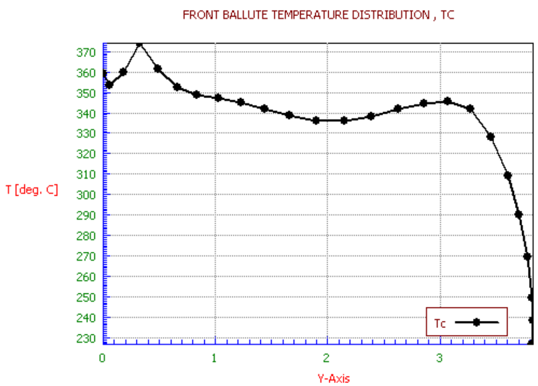
Comparison of Trajectories

Ballistic analyses utilized Cd=1, estimated from previous CFD studies for rocket ballute.
For considered trajectories maximum velocities were reached at 43..48 km range.
For the “first cut” we assumed that velocities of 925 m/s, 1010 m/s and 1095 m/s were all reached at 47 km altitude. Standard Atmosphere table for this altitude shows pressure of 1207 Pa and temperature T=274K
We performed external flow CFD simulations for on-design max.velocities.
These velocities are 925 m/s for 110 km trajectory, 1010 m/s for 120 km trajectory and 1091 m/s for 130 km trajectory.

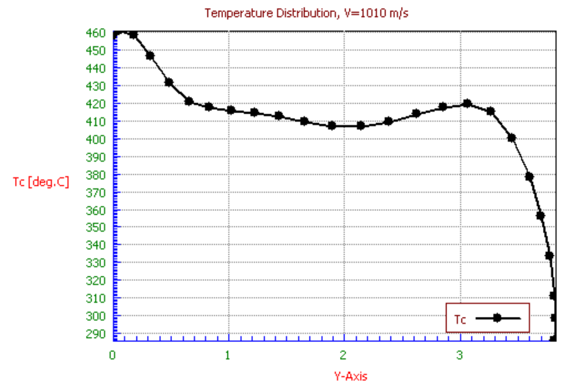
In order to perform analysis using ACE+ at high supersonic speeds lower velocity supersonic solution must be obtained first (for example at Ufreestream=500 m/s), and then used as “initial field” for conditions with higher velocities. We used intermediate solutions at 500, 650, 700 and 850 m/s.

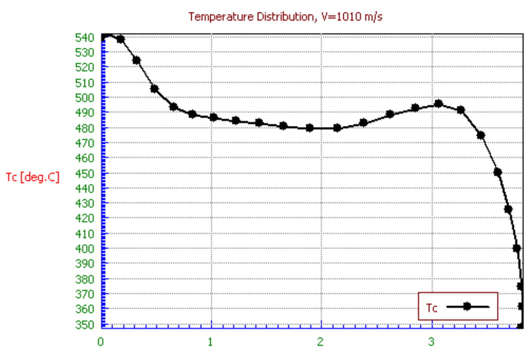
Summary: AeroHeating

110 km apogee: T peak=373 C

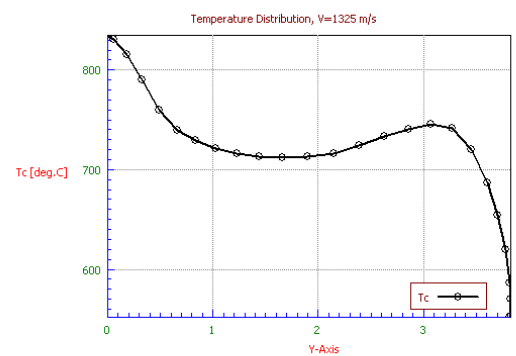


120 km apogee: T peak=461 C



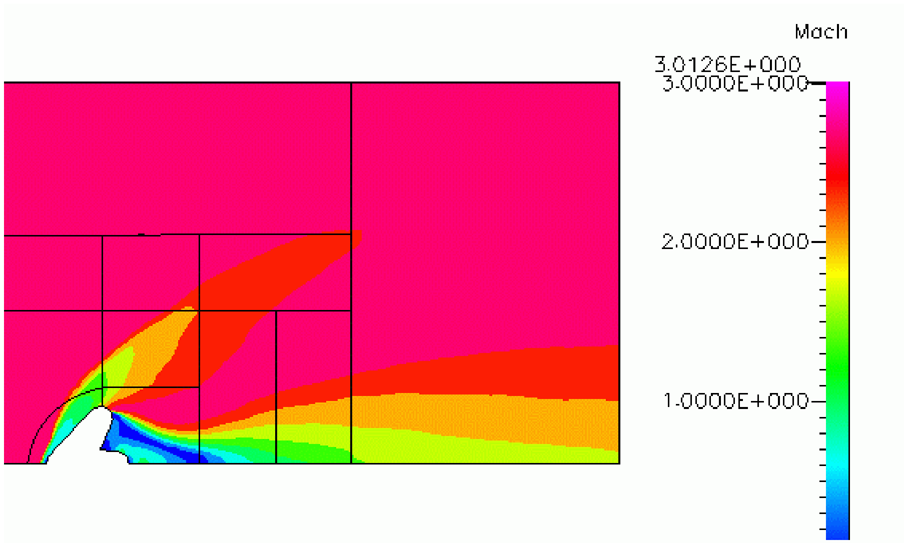


130 km apogee: T peak=543C

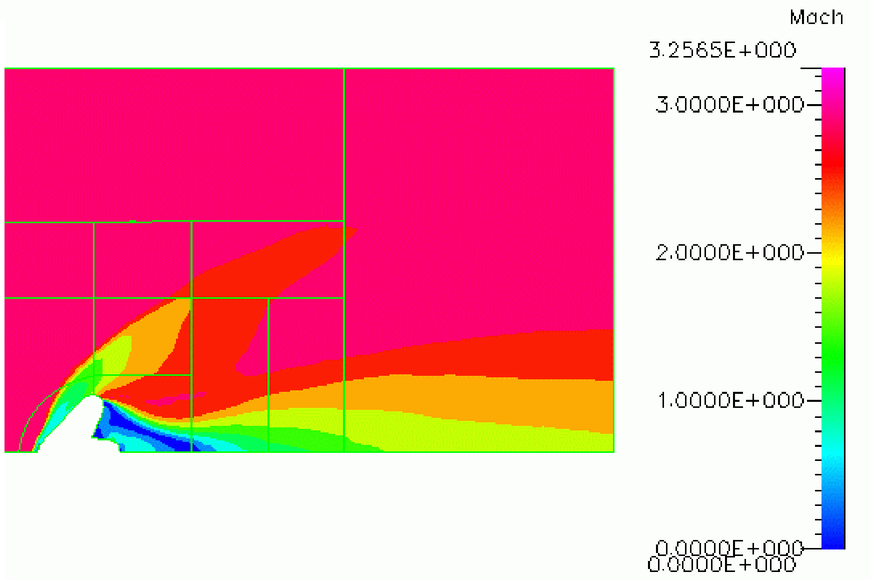


Vmax=1325 m/s; T peak=834C

MACH - V=925 m/s, H=110 km



110 km apogee, V=925 m/s



120 km apogee, V=1010 m/s

SUMMARY AND CONCLUSIONS

Comparison of aero-heating (air temperature in front of the ballute) shows significant reduction of thermal loads down to Tmax=372 C for the trajectory with 110 km apogee. This trajectory meets X-Prize requirements. Trajectory with 120 apogee is also meeting X-prize requirements and material limitations for ballute. Our main design objective will be to achieve velocities below 1000 m/s at altitudes below 45 km. Our preliminary analysis show that we can meet this objective.

-we utilized CFD-ACE+ to analyze several consecutive iterations for the design of daVinci rocket ballute;
- using CFD we were able to “zero-in” on a conceptual configuration, flight scenario and trajectory requirements that will meet X-prize objectives and also minimize thermal loads;
-estimated thermal loads (Tmax<500C) can be met with commercially available materials used by ballute manufacturers

<u>CFD Heads-up:</u>

-coupled flow, heating shell simulation
-density-based gas flow and heating simulations
-wake heating issues
-transient mission profile simulations
-capsule transient heating analysis
-ballute and air heating analysis
-coupled flow --ballute fluid-structure interaction